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Estimation of Effective Radius of Cloud Particles from the Radar Reflectivity

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ESTIMATION OF EFFECTIVE RADIUS OF CLOUD PARTICLES FROM THE RADAR REFLECTIVITY

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1. INTRODUCTION

The effect of clouds is one of the major sources of uncertainty in predicting climate change that would result from increased greenhouse gases. Slingo (1990) has suggested that for climate modelling the liquid water path (LWP) and the effective radius (r_e) should be known to a relative accuracy of 5%. In this paper we consider the feasibility of estimating these two parameters from observations of the radar reflectivity of clouds.

The size spectra of cloud droplets observed in stratocumulus and cumulus by the C-130 aircraft of the Meteorological Research Flight have been used to compute the values of radar reflectivity (Z) and effective radius (r_e) using the following relationships:

$$Z = \sum N_i D_i^6 \qquad (1)$$

$$r_e = \frac{\sum N_i r_i^3}{\sum N_i r_i^2} \qquad (2)$$

where N_i is the concentration of particles of radius r_i and diameter D_i. The cloud droplets in the diameter range 2 to 47μm were measured by the FSSP (Forward Scattering Spectrometer Probe) which sorts them into 15 size intervals. Larger drizzle drops in the range 50μm to 800μm were detected with the 2D cloud probe.

2. REFLECTIVITY AND EFFECTIVE RADIUS

Values of Z and r_e were computed from stratocumulus and cumulus droplet size spectra observed by the aircraft over the sea around the UK and also during the ASTEX project near the Azores as part of the effective radius parameterisation project. The data from 3300km of aircraft cloud penetration obtained on 15 separate days are displayed in Figure 1 for values of Z above -50dBZ. These data should provide a representative cross-section of stratocumulus clouds. On three of the fifteen days the stratocumulus was deep and drizzle droplets were detected by the 2D cloud probe in well defined regions typically 15km across. In these regions the Z values computed from the 2D cloud probe could exceed 0dBZ, but the FSSP spectra were unaffected and have been included in the analysis in Figure 1. Each of the 32722 data points plotted in this figure represents 1 second of aircraft data and is equivalent to 100m of aircraft path.

Figure 1 demonstrates a strong relationship between the two variables. When Z was plotted against $\log(r_e)$ the correlation was improved, and a least squares linear fit for the 28378 data point with Z above -40dBZ gave:

$$Z(dBZ) = -61 + 37\log(r_e) \qquad (3)$$

Data below -40dBZ are rather noisy and below the probable sensitivity of any cloud radar; they represent regions at the edges of clouds and have a negligible ($< 0.02 g\,m^{-3}$) cloud liquid water content.

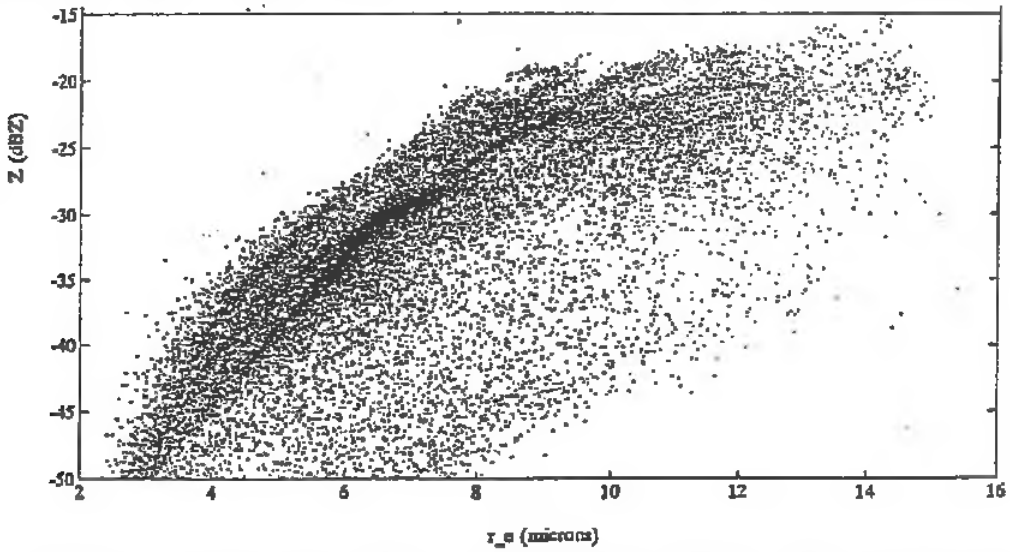

Figure 1. Values of radar reflectivity and effective radius derived from 3200km of aircraft data.

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We now consider the various factors contributing to the distribution of data points in the scattergram in figure 1. Calculations of the Poisson error in the value of Z from the finite number of particles sampled by the cloud probes contribute an error in Z of about 10%. This figure is not significant compared with the random error of about 18% in the sizing of individual particles by the FSSP which, together with the uncertainty in the measurement of droplet concentration, leads to an error approaching 3dB (100%) in the Z computation.

The standard deviation of r_e for each 2dBZ range of Z values for the data in figure 1 is about 1.4μm. This is probably an overestimate: we believe that partial filling of the 100m sample volume with cloud is responsible for the skew distribution with a few points for a given Z having much larger values of r_e. Of the 28378 points used to derive the equation, 2407, about 10%, had Z values 5dBZ below the best fit line. Most of these 2407 points are close to a cloud edge, defined as being within 1km of a Z value below -50dBZ. Partial filling of the 100m sample path with cloud will have little effect on the intensive variable r_e but will lead to a considerable reduction in the extensive variable Z.

The effect of partial filling of the sample volume with cloud can be more clearly seen in Figure 2, which is a time series through 14km of cloud during which time the aircraft descended about 400m from cloud top to cloud base. The correlation between Z and r_e of Equation 1 is clear in the general trend of the two curves, and the cloud edge effects are evident in the noise near 0km and 14km. The dip in Z between 3km and 4km is not accompanied by any significant change in r_e, but although this section of data does not appear to be near a cloud edge, the observer's log reveals that the aircraft passed in and out of the cloud top during this period.

3. REFLECTIVITY AND LIQUID WATER CONTENT

If there is a universal relationship between Z and r_e as suggested by Equation 3, then this implies that, as the effective radius of stratocumulus droplets increases, then the drop spectra also change in a reproducible manner. If this is true then it would also suggest that those points not on the best fit line in Figure 1 are due to partial filling of the sample volume by the cloud. Some support to this idea is given by the relationship derived by Sauvageot and Omar (1987) between cloud liquid water content (M in g m^{-3}) and reflectivity derived by Sauvageot and Omar (1987):

$$Z = 0.03M^{1.31} \qquad (4)$$

These data were derived for droplet spectra which were measured in cumulus near to the Pyrenees, although some stratocumulus were included. Values of M were calculated for the data in Figure 1, which are predominantly for stratocumulus but with some embedded cumulus, and a least squares fit gave the following relationship:

$$Z = 0.014M^{1.21} \qquad (5)$$

Both of these equations are for Z in the range -70dBZ to -15dBZ. The predicted values of Z are consistent, for example, an M of 0.1g m^{-3} corresponds to -28.3dBZ and -27.3dBZ for the two equations. If M were 1 g m^{-3}, rather large for stratocumulus, then the values would be -15.2dBZ and -18.5dBZ.

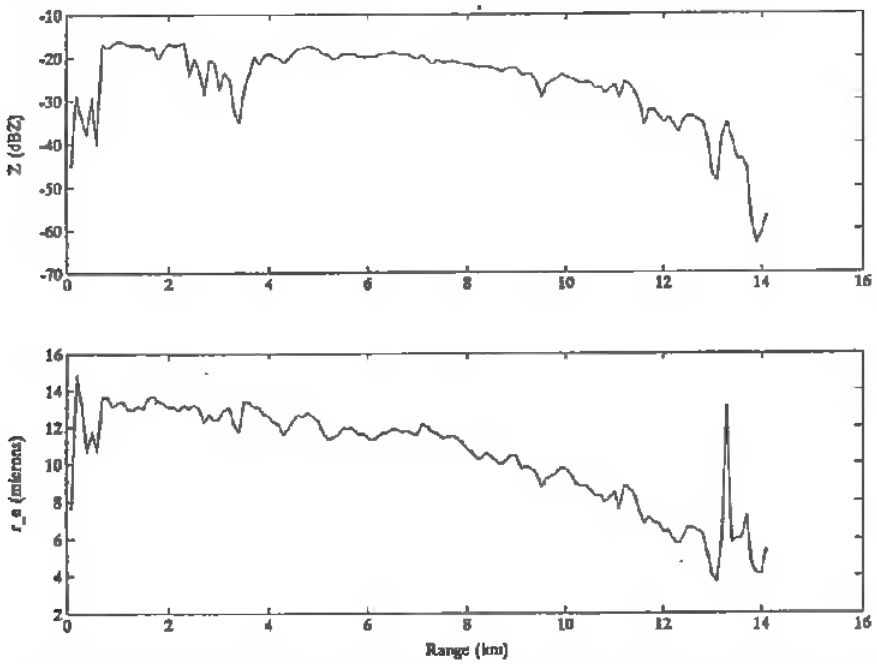

Figure 2. Radar reflectivity and effective radius for one particular aircraft penetration.

4.CONTINENTAL AND MARINE CLOUDS

In figure 3 the data have been divided into continental and maritime stratocumulus and values of Z and $\log(r_e)$ replotted from figure 1. This categorisation is somewhat subjective as all the data were actually measured over the sea. It is based on the synoptic situation, with some calculated back trajectories and measurements of aerosol concentrations. There is probably a continual transition of cloud character from marine to continental, but there were no categories to represent 'mixed' clouds. From figure 3 it is evident that values of Z and r_e are lower for the 'continental' clouds, which is to be expected because of their generally smaller droplet sizes. The data for the 'continental' clouds cluster around two straight lines: one line is similar to the data for the clouds classified as 'marine' data, but for the continental clouds there is a distinct second line with values of r_e for a given Z reduced by about 1μm; the data on this second line appear to be for truly continental clouds which comprise only a small fraction of the total data set.

5. DISCUSSION

The analyses of cloud droplet spectra in this paper suggest that the cloud reflectivity of stratocumulus provides a measure of both the effective radius (r_e) and the liquid water content of the clouds. These two parameters are important for characterising the radiative properties of such clouds. A sensitivity of -30dBZ should be sufficient to detect clouds with a liquid water content of more than 0.1 g m $^{-3}$, and effective radius above 7μm. To resolve the vertical structure of stratocumulus with radar a pulse length shorter than the depth of the cloud layer would be required.

A cloud radar operating from space with a 1km footprint would complement other cloud sensing techniques presently being developed. Taylor (1992) has shown that values of effective radius and optical depth at cloud top can be inferred from cloud top reflectance measured at 2.26μm, 1.25μm and 0.55μm (see also King et al, 1992). These passive VIS/IR techniques have the advantage of rapid scanning but will not work at night or when high clouds are present; errors may be introduced if the cloud top is uneven. The merit of a range gated radar is that it can provide a complete profile of clouds at all levels and that night time sampling enable it to sense any diurnal cloud cycle.

6. ACKNOWLEDGMENTS

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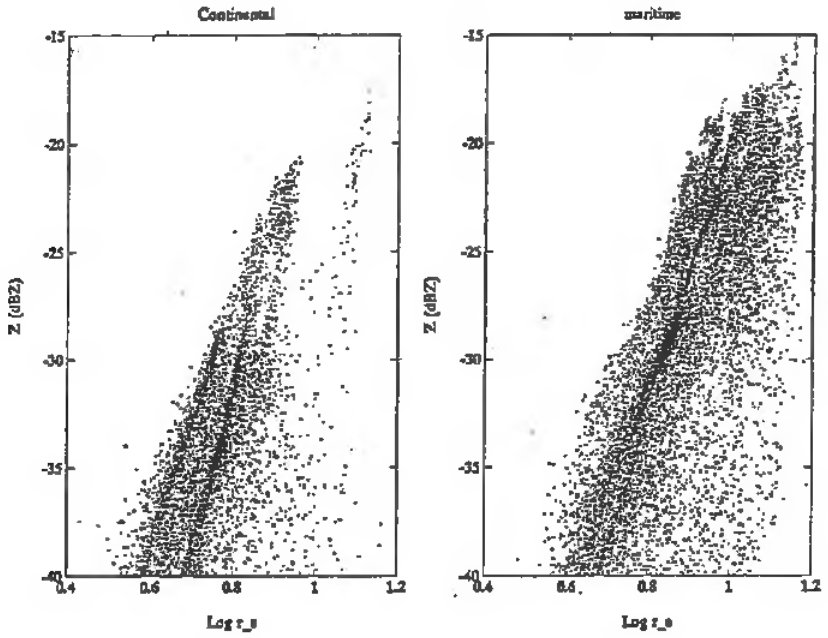

Figure 3. Division of data in Figure 1 by cloud type.

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